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(54) **SOLAR CELL WITH DELTA DOPING LAYER**

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H01L 31/0304	(2006.01)
H01L 31/0687	(2012.01)
H01L 31/0693	(2012.01)

(52) **U.S. Cl.**

CPC ***H01L 31/0735*** (2013.01); *H01L 31/0304* (2013.01); *H01L 31/03042* (2013.01); *H01L 31/0687* (2013.01); *H01L 31/0693* (2013.01); *Y02E 10/544* (2013.01)

(58) **Field of Classification Search**

CPC H01L 31/0735; H01L 31/0304; H01L 31/03042; H01L 31/0687; H01L 31/06875; H01L 31/06; H01L 31/0693

See application file for complete search history.

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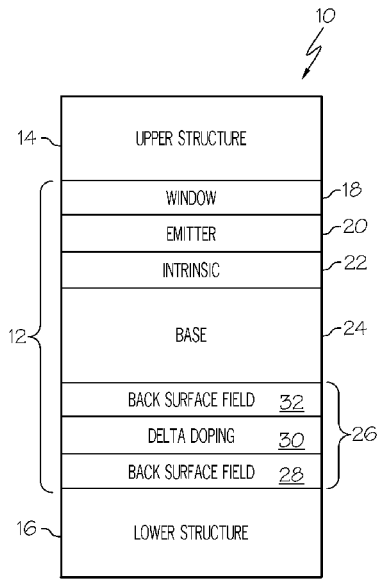
(57) **ABSTRACT**

A solar cell including a base region, a back surface field layer and a delta doping layer positioned between the base region and the back surface field layer.

8 Claims, 4 Drawing Sheets



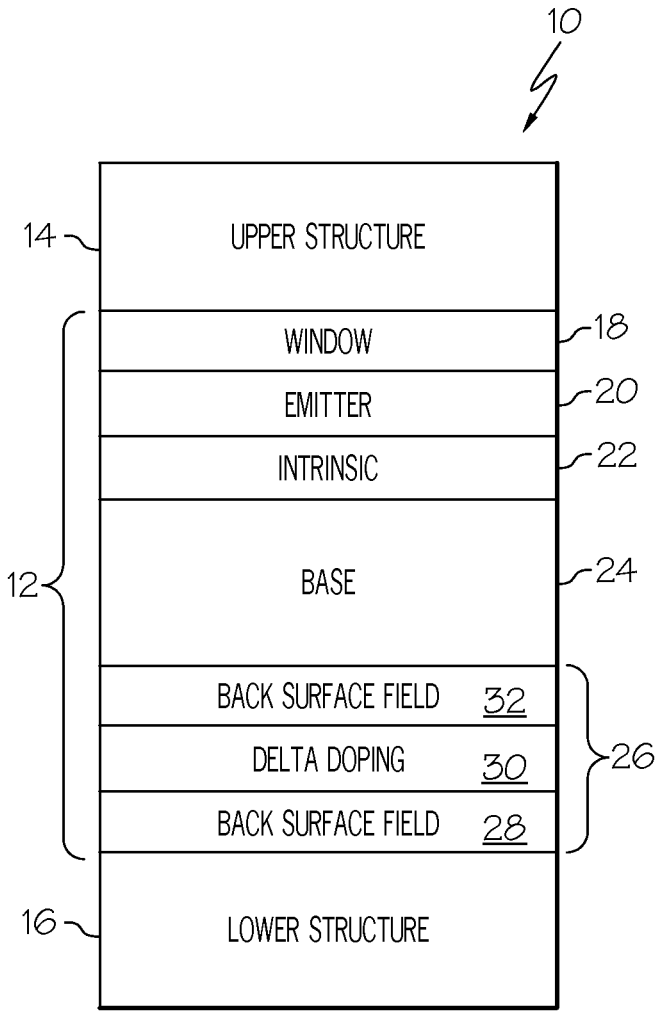

10
14
UPPER STRUCTURE
WINDOW
18
EMITTER
20
INTRINSIC
22
12
BASE
24
BACK SURFACE FIELD 32
DELTA DOPING 30
26
BACK SURFACE FIELD 28
16
LOWER STRUCTURE

FIG. 1

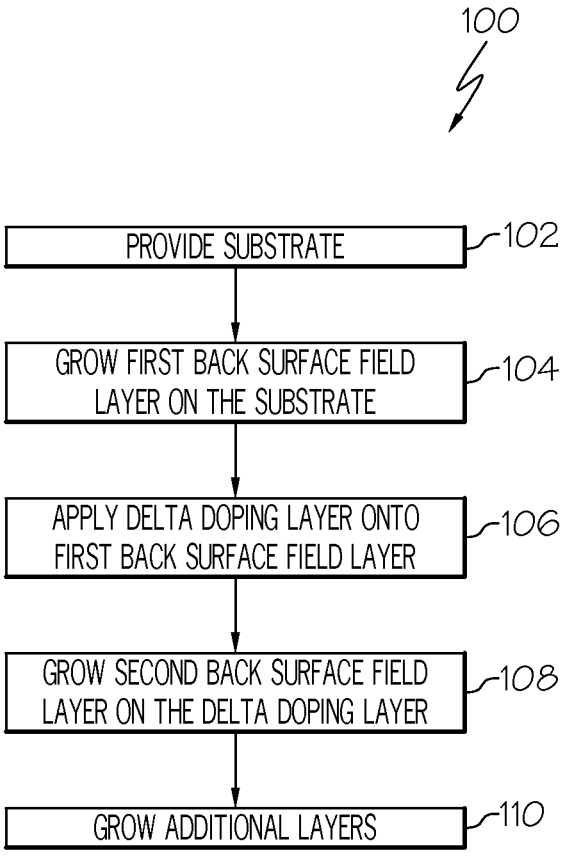

100
PROVIDE SUBSTRATE
102
GROW FIRST BACK SURFACE FIELD LAYER ON THE SUBSTRATE
104
APPLY DELTA DOPING LAYER ONTO FIRST BACK SURFACE FIELD LAYER
106
GROW SECOND BACK SURFACE FIELD LAYER ON THE DELTA DOPING LAYER
108
GROW ADDITIONAL LAYERS
110

FIG. 2

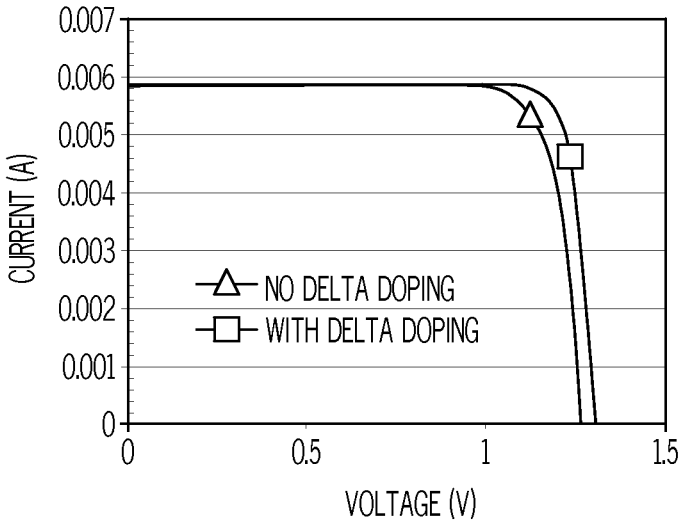

0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
CURRENT (A)
NO DELTA DOPING
WITH DELTA DOPING
0
0.5
1
1.5
VOLTAGE (V)

FIG. 3

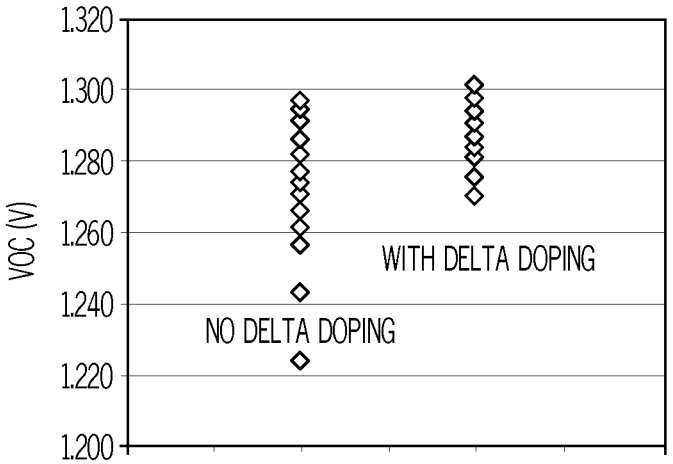

1.320
1.300
1.280
1.260
1.240
1.220
1.200
VOC (V)
WITH DELTA DOPING
NO DELTA DOPING

FIG. 4

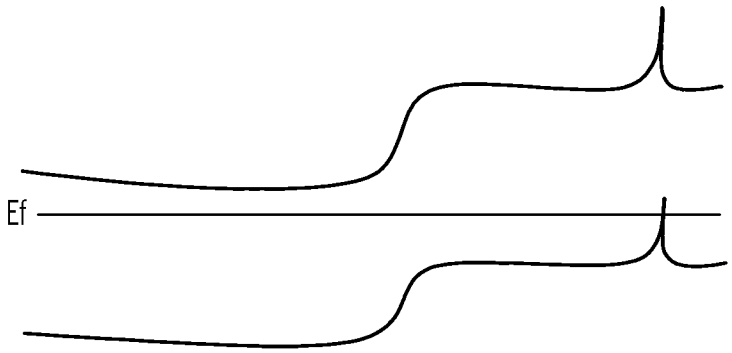


FIG. 5A

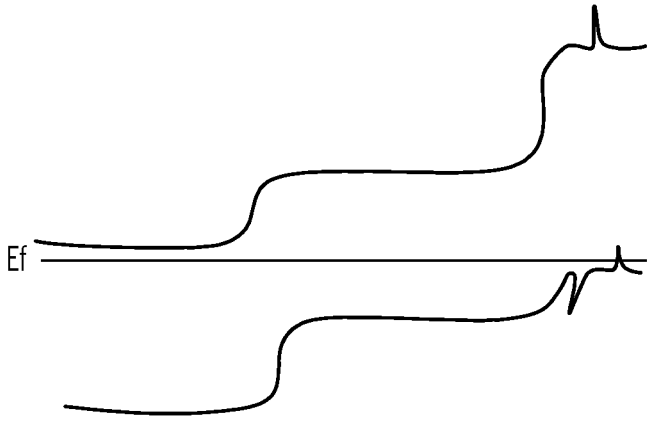


FIG. 5B

SOLAR CELL WITH DELTA DOPING LAYER

FIELD

This application relates to solar cells and, more particularly, to solar cells with a delta doping layer and, even more particularly, to solar cells with a delta doping layer in the back surface field region.

BACKGROUND

Solar cells convert the sun's energy into useful electrical energy by way of the photovoltaic effect. Modern multijunction solar cells operate at efficiencies significantly higher than traditional, silicon solar cells, with the added advantage of being lightweight. Therefore, solar cells provide a reliable, lightweight and sustainable source of electrical energy suitable for a variety of terrestrial and space applications.

A solar cell typically includes a semiconductor material having a certain energy bandgap. Photons in sunlight having energy greater than the bandgap of the semiconductor material are absorbed by the semiconductor material, thereby freeing electrons within the semiconductor material. The freed electrons diffuse through the semiconductor material and flow through a circuit as an electric current.

Electron-hole recombination at the rear surface of a solar cell results in a loss of efficiency. Therefore, solar cells are typically provided with a back surface field layer positioned proximate the rear surface of the solar cell. The back surface field layer serves as a barrier to minority carrier flow toward the rear surface (i.e., toward the tunnel junction or the rear electrode). Therefore, the back surface field layer generally prevents the minority carrier from recombining at the back interface or surface, or escaping out of the base, of the solar cell, thereby passivating the base back interface or surface and acting as a minority carrier barrier of the solar cell. Unfortunately, it is becoming increasingly difficult to find higher bandgap material to use as the back surface field layer, particularly for high bandgap solar cells, such as AlGaInP solar cells.

Accordingly, those skilled in the art continue with research and development efforts in the field of solar cells.

SUMMARY

In one embodiment, the disclosed solar cell may include a base region, a back surface field layer and a delta doping layer positioned between the base region and the back surface field layer.

In another embodiment, the disclosed solar cell may include a base region having a front end and a rear end, and a delta doping layer positioned proximate the rear end of the base region.

In yet another embodiment, disclosed is a method for forming a solar cell. The method may include the steps of (1) providing a substrate; (2) growing a back surface field layer on the substrate; (3) delta doping the back surface field layer to form a delta doping layer; and (4) growing an additional layer over the delta doping layer.

Other embodiments of the disclosed solar cell with delta doping layer and method for forming the same will become apparent from the following detailed description, the accompanying drawings and the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic cross-sectional view of one embodiment of the disclosed solar cell with delta doping layer;

FIG. **2** is a flow chart showing the steps that may be used to form the disclosed solar cell with delta doping layer;

FIG. **3** is a graphical illustration of illuminated current-voltage ("LIV") comparing the disclosed solar cell (with a delta doping layer) and a solar cell without a delta doping layer in the back surface field region;

FIG. **4** is a graphical illustration of open-circuit voltage of the disclosed solar cell (with a delta doping layer) and, for comparison, a solar cell without a delta doping layer in the back surface field region;

FIG. **5**A is a schematic bandgap diagram of a solar cell having a delta doping layer alone as the back surface field region; and

FIG. **5**B is a schematic bandgap diagram of a solar cell having a delta doping layer as part of the back surface field region.

DETAILED DESCRIPTION

Referring to FIG. **1**, one embodiment of the disclosed solar cell with delta doping layer, generally designated **10**, may include a cell **12** positioned between an upper structure **14** and a lower structure **16**. The cell **12** may include a window **18**, an emitter region **20**, an intrinsic or depletion region **22**, a base region **24** and a back surface field ("BSF") region **26**.

The upper structure **14** may be any structure positioned over the cell **12**. Those skilled in the art will appreciate that the specific composition of the upper structure **14** will depend on the specific construction of the solar cell **10**.

In one construction, the solar cell **10** may be a multijunction solar cell and the cell **12** may be the upper subcell of the multijunction solar cell. Alternatively, the cell **12** may be the only cell of the solar cell **10**. Therefore, the upper structure **14** may include, for example, an anti-reflective coating layer, a cap layer (e.g., a GaAs cap) and an electrical contact layer (e.g., a metal grid).

In another construction, the solar cell **10** may be a multijunction solar cell and the upper structure **14** may be another subcell of the multijunction solar. Those skilled in the art will appreciate that adjacent subcells may be separated by a tunnel junction.

The lower structure **16** may be any structure positioned below the cell **12**. Those skilled in the art will appreciate that the specific composition of the lower structure **16** will depend on the specific construction of the solar cell **10**.

In one construction, the solar cell **10** may be a multijunction solar cell and the cell **12** may be the lower subcell of the multijunction solar cell. Alternatively, the cell **12** may be the only cell of the solar cell **10**. Therefore, the lower structure **16** may include, for example, a buffer layer and a substrate (e.g., a germanium substrate).

In another construction, the solar cell **10** may be a multijunction solar cell and the lower structure **16** may be another subcell of the multijunction solar. Cell **12** may be separated from the underlying cell by a tunnel junction.

The back surface field region **26** may include a first back surface field layer **28**, a delta doping layer **30** and a second back surface field layer **32**. Therefore, the delta doping layer **30** may be positioned between the first back surface field layer **28** and the second back surface field layer **32**.

Alternatively, the back surface field region **26** may include the first back surface field layer **28** and the delta doping layer **30** (i.e., no second back surface field layer). Therefore, the the delta doping layer **30** may be positioned at the interface between the base region **24** and the first back surface field layer **28**.

The delta doping layer **30** may be comprised of any element that behaves as a dopant with respect to the first and second back surface field layers **28**, **32**. Therefore, the composition of the delta doping layer **30** may depend on the composition of the first and second back surface field layers **28**, **32**.

As one general and non-limiting example, the cell **12** may be formed as follows: the window **18** may be $AlInP_2$, the emitter region **20** may be $GaInP_2$, the intrinsic region **22** may be $GaInP_2$, the base region **24** may be $GaInP_2$, and the first and second back surface field layers **28**, **32** may be AlGaAs. Therefore, since the first and second back surface field layers **28**, **32** are formed from Group 13 and 15 elements, the delta doping layer **30** may be formed from an element (or elements) other than the elements in Groups 13 and 15.

As one specific and non-limiting example, the first and second back surface field layers **28**, **32** of the cell **12** may be formed from AlGaAs and the delta doping layer **30** may be formed from a Group 14 element, such as carbon, silicon or germanium.

As another specific and non-limiting example, the first and second back surface field layers **28**, **32** of the cell **12** may be formed from AlGaAs and the delta doping layer **30** may be formed from carbon.

The layer thickness of the delta doping layer **30** may depend on various factors, including the type of delta dopant used and the back surface field material (e.g., the material of the first back surface field layer **28**) upon which the delta doping layer **30** is applied. Those skilled in the art will appreciate that the limitations of delta doping may limit the overall layer thickness of the delta doping layer **30** that may be achieved.

In one expression, the delta doping layer **30** may have an average layer thickness ranging from about 1 nanometer to about 100 nanometers. In another expression, the delta doping layer **30** may have an average layer thickness ranging from about 5 nanometers to about 50 nanometers. In another expression, the delta doping layer **30** may have an average layer thickness ranging from about 5 nanometers to about 25 nanometers. In another expression, the delta doping layer **30** may have an average layer thickness ranging from about 5 nanometers to about 15 nanometers. In yet another expression, the delta doping layer **30** may have an average layer thickness of about 10 nanometers.

Thus, the delta dopant may be confined to a very thin layer in the back surface field region **26**.

The bulk concentration of delta dopant in the delta doping layer **30** may also depend on various factors, including the type of delta dopant used and the material of the substrate (e.g., the material of the first back surface field layer **28**) upon which the delta doping layer **30** is applied.

In one expression, the bulk concentration of delta dopant in the delta doping layer **30** may be at least about 1×10^{18} atoms per cm^3. In another expression, the bulk concentration of delta dopant in the delta doping layer **30** may be at least about 1×10^{19} atoms per cm^3. In another expression, the bulk concentration of delta dopant in the delta doping layer **30** may be at least about 1×10^{20} atoms per cm^3. In another expression, the bulk concentration of delta dopant in the delta doping layer **30** may be at least about 1×10^{21} atoms per cm^3. In yet another expression, the bulk concentration of delta dopant in the delta doping layer **30** may range from about 1×10^{18} atoms per cm^3 to about 1×10^{22} atoms per cm^3.

FIG. **2** is a flow chart that depicts the steps of one particular aspect of the disclosed method, generally designated **100**, for forming the disclosed solar cell with delta doping layer. Other methods for forming a delta doping layer proximate the rear of a solar cell are also contemplated.

The method **100** may begin at block **102** with the step of providing a suitable substrate. The substrate may be any substrate upon which a back surface field layer may be grown. One non-limiting example of a suitable substrate is germanium.

At block **104**, a first back surface field layer may be grown on the substrate. The step of growing the first back surface field layer (step **104**) may continue until the desired cross-sectional thickness of the first back surface field layer has been achieved.

The first back surface field layer may be grown by epitaxy, such as molecular beam epitaxy, metalorganic vapor-phase epitaxy or chemical vapor-phase epitaxy. The epitaxy precursors may be selected to yield the desired material of the first back surface field layer.

Optionally, prior to the step (block **104**) of growing the first back surface field layer, a buffer may be applied to the substrate such that the buffer is positioned between the first back surface field layer and the substrate. Those skilled in the art will appreciate that a buffer may be selected to minimize or eliminate the effects of lattice mismatch between the first back surface field layer and the substrate.

At block **106**, epitaxy may be halted and delta doping may begin. During the delta doping step (block **106**), the desired delta dopant may be introduced to form a delta doping layer on the first back surface field layer. The delta doping step (block **106**) may be performed until a predetermined minimum bulk concentration of the delta dopant in the delta doping layer has been achieved.

At block **108**, delta doping may be halted and growth of the second back surface field layer may begin. The second back surface field layer may be grown by epitaxy until the desired cross-sectional thickness of the second back surface field layer has been achieved.

With the back surface field layers and the delta doping layer formed, the method **100** may continue with the step of growing additional layers of the solar cell, such as the base region, the intrinsic region, the emitter region and the window **18**, as shown at block **110**.

Thus, two solar cells were assembled using the method **100**: one with a delta doping layer in the back surface field region and one without a delta doping layer. Both solar cells were generally identical other than either the presence or absence of the delta doping layer. As shown in FIGS. **3** and **4**, the solar cell with a delta doping layer exhibits higher open circuit voltage ("V_{OC}") and a better fill factor.

FIGS. **5**A and **5**B are schematic band diagrams of two solar cells with delta doping as part the back surface field region. FIG. **5**A is the band diagram of a solar cell in which the delta doping layer is the only back surface field layer. FIG. **5**B is the band diagram of a solar cell in which the delta doping layer is in addition to the higher bandgap back surface field layer. In FIG. **5**A, the delta doping layer introduces a band energy spike, and this energy spike blocks the minority carrier from escaping away from the p-n junction. In FIG. **5**B, the delta doping layer-induced energy spike reinforces the back surface field function of blocking the minority carrier.

When the delta doping layer is positioned at the interface of the base region and the back surface field layer, the delta doping layer may passivate better at the interface and, therefore, may reduce the interface recombination, which may also improve the back surface field function.

Furthermore, by positioning the delta doping layer in the back surface field region, the highly p-type delta doping layer may be very well confined in a narrow material thickness

range such that p-dopant back-diffusion into the base region is of little or no concern. Those skilled in the art will appreciate that diffusion of dopant into the base region can hurt cell performance by shortening the minority carrier diffusion length.

Accordingly, solar cell efficiency may be improved by using a delta doping layer in the back surface field region of the solar cell. Without being limited to any particular theory, it is believed that using a delta doping layer in the back surface field region may render the back surface field region more efficient at blocking the minority carrier in the solar cell base and may passivate better at the interface between the base region and the back surface field region. It is further believed that using a delta doping layer in the back surface field region may be particularly useful for high bandgap solar cells in which it is hard to find a higher bandgap material to use as the back surface field.

In another, alternative embodiment, the disclosed delta doping layer may be incorporated into the base region, rather than the back surface field region, of the solar cell. The base region may include a front end and a rear end. The delta doping layer may be incorporated into the base region proximate (i.e., at or near) the rear end of the base region.

Although various embodiments of the disclosed solar cell with delta doping layer have been shown and described, modifications may occur to those skilled in the art upon reading the specification. The present application includes such modifications and is limited only by the scope of the claims.

What is claimed is:

1. A solar cell comprising:

a base region including an active junction, said base region comprising a first side and a second side opposed from said first side;

an intrinsic region directly contacting said first side of said base region;

an emitter region located on said first side of said base region and directly contacting said intrinsic region such that said intrinsic region is located between said base region and said emitter region;

a delta doping layer directly contacting said second side of said base region, said delta doping layer comprising a dopant selected from the group consisting of carbon, silicon, germanium, tin, lead and combinations thereof, wherein said delta doping layer comprises an average layer thickness ranging from about 5 nanometers to about 15 nanometers, wherein said delta doping layer comprises said dopant at a concentration of at least 1×10^{19} atoms per cm^3; and

a back surface field layer comprising AlGaAs or AGaInP, said back surface field layer directly contacting a surface of said delta doping layer opposite said base region such that said delta doping layer is disposed directly contacting and between said base region and said back surface field layer.

2. The solar cell of claim **1** wherein said delta doping layer comprises dopant at a concentration of at least 1×10^{20} atoms per cm^3.

3. The solar cell of claim **1** formed as a multijunction solar cell.

4. The solar cell of claim **1** further comprising a window, wherein said emitter region is positioned between said base region and said window.

5. A solar cell comprising:

a base region including an active junction, said base region comprising a first side and a second side opposed from said first side;

an intrinsic region directly contacting said first side of said base region;

an emitter region located on said first side of said base region and directly contacting said intrinsic region such that said intrinsic region is located between said base region and said emitter region;

a first back surface field layer located on said second side of said base region, said first back surface field layer comprising AlGaAs or AlGaInP;

a second back surface field layer located on said second side of siade base region, said second back surface field layer comprising AlGaAs or AlGaInP; and

a delta doping layer positioned between and directly contacting said first back surface field layer and said second back surface field layer, said delta doping layer comprising a dopant selected from the group consisting of carbon, silicon, germanium, tin, lead, and combinations thereof, wherein said delta doping layer comprises and average layer thickness ranging from 5 nanometers to about 15 nanometers, wherein said delta doping layer comprises said dopant at a concentration of at least 1×10^{19} atoms per cm^3.

6. The solar cell of claim **5**, wherein said delta doping layer comprises dopant at a concentration of at least 1×10^{20} atoms per cm^3.

7. The solar cell of claim **5** formed as a multijunction solar cell.

8. The solar cell of claim **5**, further comprising a window, wherein said emitter region is positioned between said base region and said window.

* * * * *